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AN AERODYNAMIC LOAD CRITERION FOR AIRSHIPS

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ABSTRACT: This paper derives a simple aerodynamic bending moment envelope for conventionally shaped airships. This criterion is intended to be used, much like the Naval Architect's "standard wave," for preliminary estimates of longitudinal strength requirements. It should be useful in trade-off studies between speed, fineness ratio, block coefficient, structure weight, and other such general parameters of airship design.

INTRODUCTION

The longitudinal, or beam, strength of an airship is obviously of fundamental importance to its design. It would be of great convenience to the designer, therefore, to have an envelope of the maximum bending moment distribution over the airship's length. This paper derives such an envelope from theories and experiments in the literature, and attempts to show that it is neither uneconomically severe nor rashly lenient.

In the early days of airships, speeds and dynamic pressures were low, and static loads were the major ones to be resisted by the hull beam. By the end of World War I, however, performance had improved so that aerodynamic loads were as important as, or even preponderant over, static loads. This was made dramatically evident by the succession of large airships which were lost as the result of aerodynamic over-

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loading of their longitudinal strength. R-38 in 1921 focused attention on circling flight and sudden extreme control maneuvers. Shenandoah in 1925 emphasized the hazards of strong vertical gusts. Finally, although Macon had been designed with gust effects in mind, her loss by fin failure in 1935 led to a critical review of airship design and contruction by the Durand Committee. This review concluded that there was insufficient understanding of the effects of gust loads, both as regards overall structural loads and local fin loads.

At the recommendation of the Durand Committee, the Navy contracted with the Daniel Guggenheim Airship Institute (DGAI) to conduct a broadly based study of this problem. The results of this study up to 1940 are summarized in Reference 1; they comprise wind tunnel, whirling arm, and water tunnel experiments on airship models, and a meterological investigation of atmospheric gustiness.

The essential elements of a correct theoretical approach had already been established in 1935 (References 2 and 3). But the actual work of setting up the equations, obtaining a solution, and finding quantitative results was not completed and published until 1958, when Calligeros and McDavitt reported work they had performed at M.I.T. under contract to the Bureau of Aeronautics.[4]

The larger part of this paper will consist of a description of the Calligeros-McDavitt theory and its numerical results, and of the DGAI experiments, with a comparison and reconciliation of the two. From the joint theoretical and experimental results, an overall gust moment envelope is constructed. Examples of the other types of aerodynamic loads -- circling flight, abrupt control reversal, and lifting dynamically a static overload -- are presented from the literature. They are shown all to fall within the gust moment envelope, which to some extent justifies the scant attention paid them here. This result also establishes the gust moment envelope as the aerodynamic load criterion advertised in the title.

Bending moments are generalized in the usual way, as a dimensionless coefficient defined by:

$$\text{Bending Moment} = C_m \, q \, (\text{Vol})^{2/3} L \tag{1}$$

where (Vol) is air volume, L length, and q dynamic pressure.

A discussion in terms of a discrete gust seems somewhat outmoded in comparison with the methods of spectral analysis common in airplane and missile aerodynamics, but is made necessary by the nature of the DGAI experiments. The powerspectral analysis would seem particularly appropriate for large airships, the lengths of which approach the commonly accepted value of the scale of turbulence in the free atmosphere. Happily, Reference 4 embraces both methodologies, and the agreement which is found between the discrete-gust formulation and the DGAI experiments lends confidence to the turbulent-spectrum approach.

THEORY

The theory develops the equations of motion of the airship in the usual manner. The physical situation is as pictured in Figure 1. The airship, at some angle of pitch θ and velocity V_0 is encountering a gust characterized by a spatial distribution of transverse velocities W which can be specified quite generally. In the worked numerical example, the gust form is taken as a full cycle 1 - cosine with peak velocity W_0 any specified fraction of V_0 and wavelength any given fraction of the ship length. The aerodynamic forces and moments acting on the airship are resolved into longitudinal, lateral, and rotation components, and the amount by which each set is unbalanced is equated to the acceleration multiplied by the apparent mass (or apparent moment of inertia).

The typical small-displacement linearizations of aerodynamics are then assumed, i.e., that transverse and rotary components are independent and their coefficients are directly proportional to angle of attack, angular velocity, etc. Both local aerodynamic forces and integrated aerodynamic stability derivatives are based on a modification of slender-body theory applied to the apparent cross-section distribution (i.e., including added-mass effects) taking as the base area the apparent cross-section of hull-plus-fins at the trailing edge. The equations can then be put into a dimensionless form suited to numerical solution, for any given airship form and gust assumption.

As part of the determination of the equations of motion, the local aerodynamic loads are found; these, together with the inertial reactions of the distributed airship mass, are treated as loads on a free beam, integrated to obtain shears, and again to find the bending moment curve of the beam. This theory yields, for selected stations along the airship beam, a history of the bending moment at that station as a function of the position of the airship with respect to penetration of the gust. The envelope of the maxima of the moments at these various stations would then be the design bending moment criterion we seek, if the theory were complete and exact. Other information obtainable from the theory includes the envelope of shear maxima, the lateral and angular positions of the airship and the derivatives of these quantities, and the local angle of attack and transverse acceleration at the fin center of pressure.

Reference 4 also derives transfer functions for the airship responses and loads which, applied to an assumed or empirical random gust spectrum, yield RMS values of the displacements, velocities, accelerations, shears, moments, etc.

The theoretical calculations just outlined were carried out for an airship approximating to the ZPG-2W class of million-cubic-foot nonrigids. It was found that C_m is directly proportional to W_0/V_0, the ratio of peak gust velocity to forward velocity. The history of moment at any station is dependent on the ratio of the gust development length to the length of the airship, and peaks for a ratio of 1/2, although this maximum does not vary greatly between 1/4 and 3/4. Reference 4 only calculates the case of zero rudder angle.

The full-line curve in Figure 2 is the envelope of peak values of $\frac{C_m}{W_0/V_0}$ for the example airship.

DGAI EXPERIMENTAL PROGRAM

The DGAI tests measured the motions and resultant stresses which occur when an airship moves freely under the influence of gusts. These tests were made with self-propelled models in a water tank, a transverse current of controlled velocity profile simulating the gust. The gust profile approximated a one-minus-cosine transition over a scale length of 400 feet, followed by a steady region at the full transverse velocity W_0. Model dimensions, and moments of inertia about all three axes, were scaled directly from the Akron.

The experiments reported in Reference 1 were made with "Mark II" control surfaces, scaled directly from those actually used on the Akron. Later experiments [5,6] used other sizes and shapes of surfaces. Except in one case the maximum gust moments measured with these other surfaces all fell within the envelope established by the Mark II surfaces. The exceptional fins were of very high aspect ratio (for airship fins) and placed very far aft; their high moment values were only slightly above the Mark II envelope over the rear quarter of the model, and will be ignored for our simple design rule-of-thumb.

In addition to the measurements of 6:1 fineness ratio, a few results are available on a model of equal displacement and similar profile, scaled to a 4:1 fineness ratio.

COMPARISON AND RECONCILIATION

The results of the water tunnel experiments are plotted in Figure 2. The zero-rudder bending moments for the 4:1 model are shown as crosses, and those for the 6:1 model with Mark II fins as circles. The small dots are moments on the 6:1 model when the rudder was not at zero, or was changing, during the test. Also plotted in this figure is the moment envelope of Calligeros and McDavitt's example airship, also with rudder fixed at zero.

Several observations can be made. First, there is good agreement between the measured coefficients for the 4:1 model and the theoretical curve for the nonrigid. Second, although the envelope of moments over the forebodies is virtually the same for all three airships, the coefficients over the afterbodies are markedly higher for the two rigid airships' models in comparison with the theory. Furthermore, this difference is more marked for the 6:1 model than the 4:1 model. Third, use of rudders during the gust encounter is seen to increase negligibly the envelope over the forward two-thirds of the ship, and in fact may greatly reduce the moments over this part of the ship. Only just forward of the fins does the use of the rudders increase the moment significantly, by up to 40 per cent. On the other hand, reductions of as much as 50 per cent may also result even at this far-aft station.

The agreement between theory and experiment increases confidence in both, but it is still necessary to explain the discrepancies. Three factors suggest themselves: inadequacies of theory, differences between nonrigid and rigid airships, and differences in the assumed gust shapes.

The approximations mentioned in discussing the theory are, of course, inadequacies. The small displacement linearization of the equations is significantly in error, because the displacements are not small and the aerodynamic coefficients are not constant; the rotary derivatives, for example, have been shown to have a strong dependence of angle of attack.[7] The use of modified slender-body theory, although a good approximation for obtaining the airship motions, is quite incapable of expressing the generation of distributed lift over the afterbody and the downwash of the hull upon the empennage, i.e., the local dynamic loading in the area where theory differs most from experiment.

The only notable difference between the theoretical nonrigid and the rigid models is in mass distribution, which in the nonrigid is highly peaked in the vicinity of the center of buoyancy. This might make the nonrigid more quick to respond in pitch and thus accelerate away from the gust more rapidly, before the fins were in the transverse flow. However, the difference in terms of the ratio of radius of gyration to length is only about ten per cent between nonrigid and the 6:1 model, so this effect is probably not a major one.

A third explanation of the envelope differences is found in the gust forms. The theoretical calculation assumes a full-cycle 1-cosine profile, while the profile actually achieved in the water tank approximated a half-cycle; both were about equally proportioned to ship length. Thus, when the theoretical airship had penetrated a full ship length from the entry to the gust, its lateral velocity had almost peaked and was rapidly damped out thereafter, while the rigid models at the same stage had not yet achieved their final lateral velocity, but were still accelerating in a cross-flow. This would cause the same aerodynamic loading on the rigid models as in nonequilibrium pitched flight, resulting in a bending moment in the same sense as the transient moment cause by the gust.

These physical arguments give qualitative assurance, at least, that the sign of the difference between theory and experiment is correct. On these bases, a safe envelope for gust bending moment coefficients, in terms of $C_m/W_0/V_0$, will be bounded by straight lines starting at 0 at the nose of the airship, increasing to 0.065 at 0.3 length, then to 0.10 at 0.5 length, constant to 0.65 length, and then decreasing linearly to 0 at the stern.

EXAMPLES

In order to compare the gust bending moment with other hull bending moments, it is necessary to adopt some definite value for the maximum gust velocity. The DGAI summary report, considering all available published data on gustiness as well as fresh information obtained by DGAI, concluded: "It is suggested that 35 ft/sec cross wind should be considered as a maximum value which might occur in weather conditions whose severity is not necessarily recognized even by a skilled pilot." More recent data do not seem to require much change.

The remaining two figures plot some examples of the bending moment envelope derived here against various measured or calculated airship aerodynamic moments. Figure 3 groups a number of such results for the U.S.S. Shenandoah, to which fairly extensive data are available in the literature. The Shenandoah's top speed was 91 ft/sec, which with 35 ft/sec maximum gust velocity gives W_0/V_0 equal to 0.385, so the peak of the moment coefficient envelope is 0.0385. At an altitude where atmospheric density is 0.0021 slugs/cubic ft, the corresponding bending moment is 3,950,000 lb-ft.

Curve L is a dynamic lift case, taken from Burgess' Airship Design.[8] It results in about 50 per cent greater moments than were actually ever contemplated in the Shenandoah design.[9] Curve A represents a modification of L, following a suggestion by Arnstein[10] that the maximum bending envelope could be derived from that for maximum dynamic lift by multiplying by a load factor increasing elliptically from 1 at mid-length to 3 at the ends. Curve C represents circling flight at full speed at a radius of 3,000 feet, based on curved model tests.[7] Curve R is for sudden rudder reversal, based on a control surface normal-force coefficient of 0.4, which is probably as much as can be obtained by deliberate maneuvers. The curve labeled N is a rule-of-thumb due to Naatz[11] that the maximum value of C_m is approximately 0.01; presumably this will fall off to zero at the ends according to some curve such as shown. Curve G results from a Goodyear report[12] which states that gust loads "for conventional airships" have long been calculated by using an effective angle of attack of twice the arc tangent of W_0/V_0, on the basis of two exceptional measurements of such high angles in the DGAI water tank tests. Curve X is that calculated by Burgess[9] as possibly corresponding to the conditions which broke the Shenandoah's hull at Frame 125. Point LW represents a maximum-power turning moment on a theory due to Lewitt.[13] Point B is an actual measurement by Burgess while the Shenandoah was flying over the Alleghenies in rough weather.[9]

Figure 4 collects together data on four airships, together with their bending moment criteria as derived here. Points labeled LA-T, LA-R (which are indistinguishable) and LA-G are, respectively, moments measured on the Los Angeles in steady turning, sudden rudder reversal, and flight through gusty weather. (14) Point RS-1 is a measured moment at the midpoint of the keel of the U.S. Army semirigid RS-1,[16] when encountering a gust which caused pitching through $\pm 25°$. A curve is presented for moments due to rudder reversal calculated by Schwengler for a 7,000,000 cubic foot paper design.[15] Finally, the design bending moment curve for the Akron[1] is shown, the only one which anywhere exceeds the proposed moment criterion.

The weight which ought to be given to these examples differs widely in the various cases. However, the fact that virtually all lie completely within the gust moment criterion derived here, and that the most severe of the examples approach rather closely that criterion, does give some credibility to the contention that the simple

envelope given is a useful rule-of-thumb for determining the preliminary longitudinal strength requirements of new airship designs.

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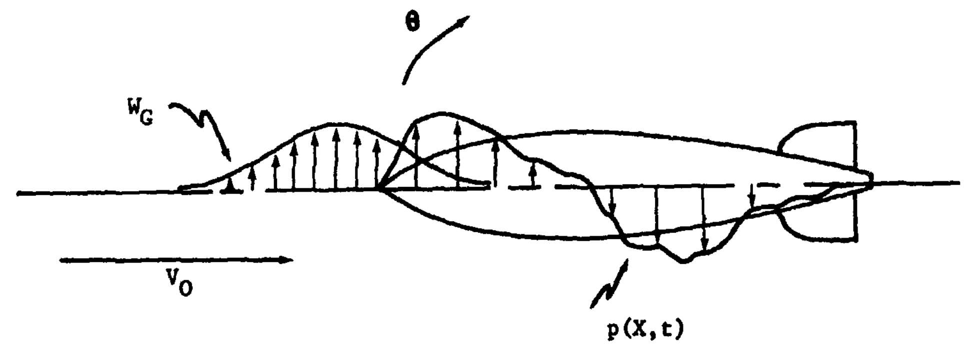

FIGURE 1. LOADING DIAGRAM OF AIRSHIP

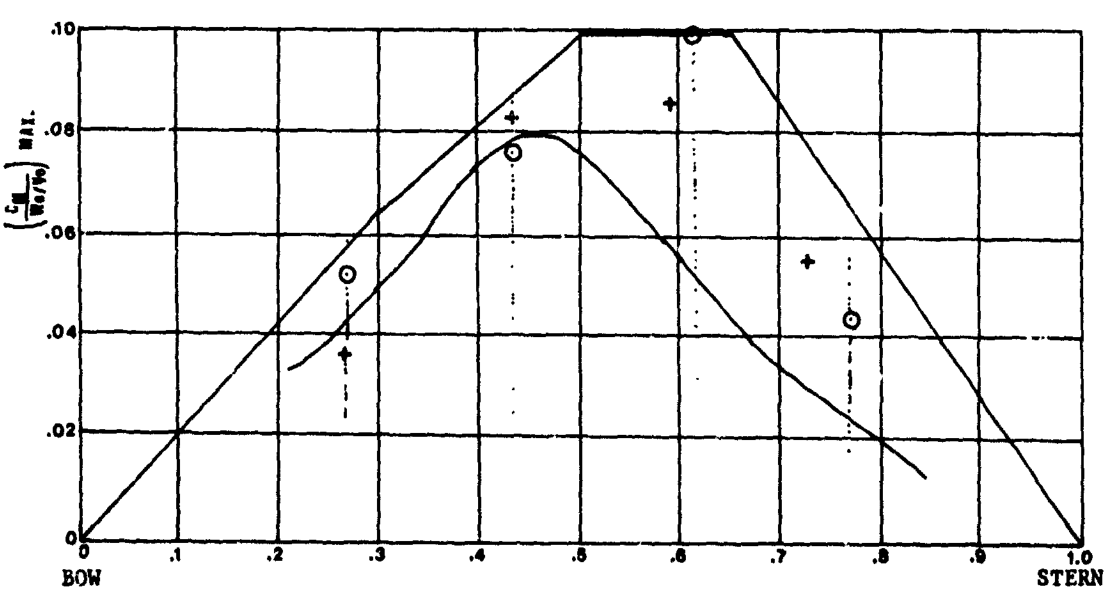

FIGURE 2. ENVELOPE OF MAXIMUM BENDING MOMENT COEFFICIENTS

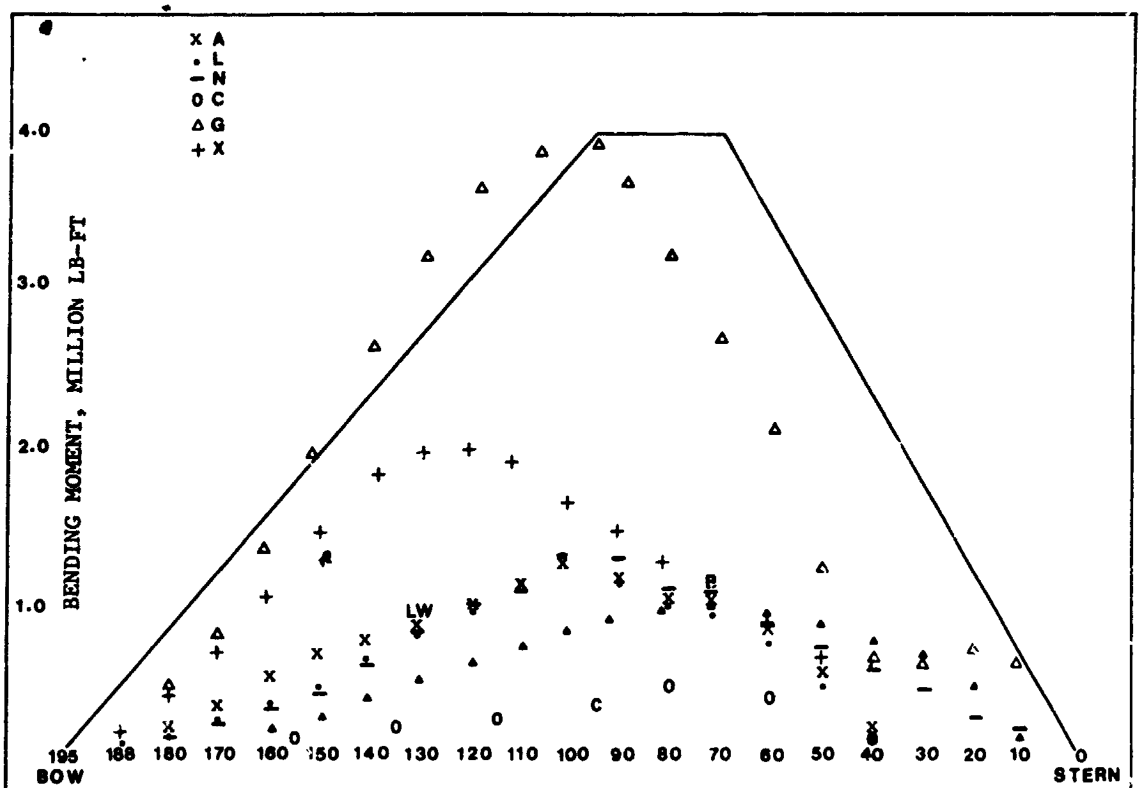

FIGURE 3. SHENANDOAH MOMENTS

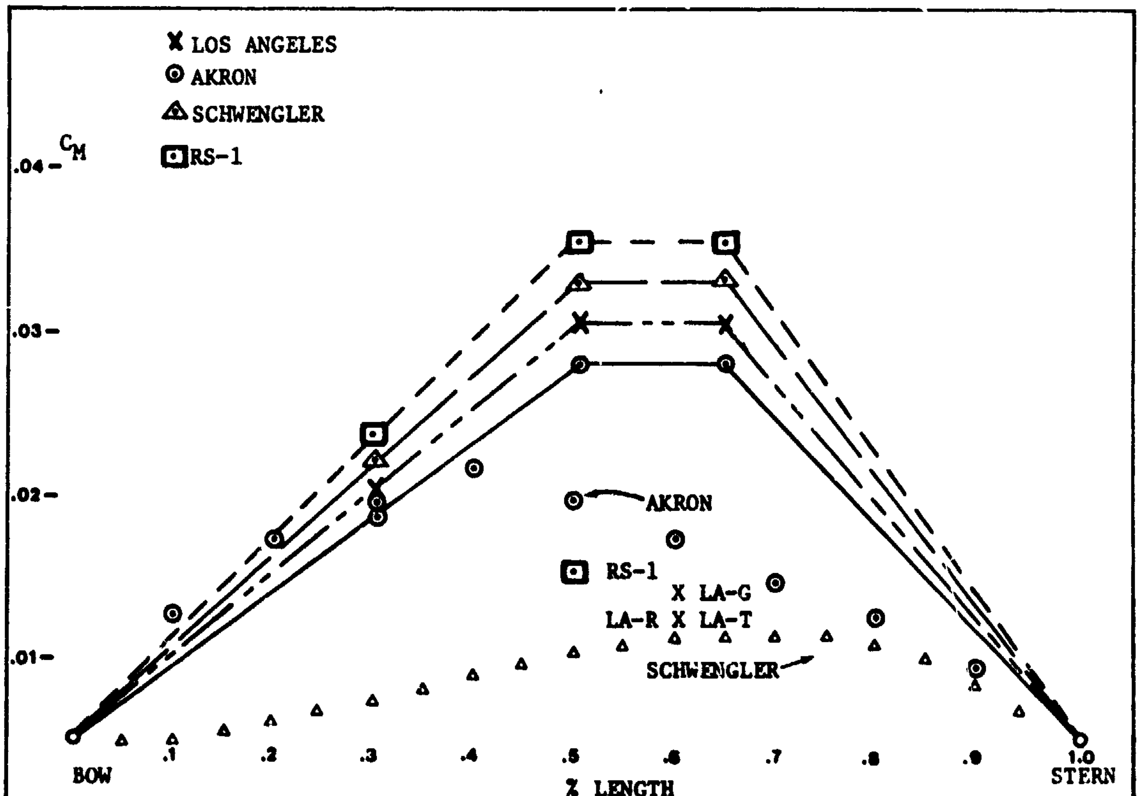

FIGURE 4. VARIOUS BENDING MOMENT EXAMPLES